

# INTRODUCTION TO THE SPECIAL ISSUE ON SCIENTIFIC BALLOON CAPABILITIES AND INSTRUMENTATION

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In 1783, the Montgolfier brothers ushered in a new era of transportation and exploration when they used hot air to drive an untethered balloon to an altitude of ~2 km. Made of sackcloth and held together with cords, this balloon challenged the way we thought about human travel, and it has since evolved into a robust platform for performing novel science and testing new technologies. Today, high-altitude balloons regularly reach altitudes of 40 km, and they can support payloads that weigh more than 3,000 kg. Long-duration balloons can currently support mission durations lasting ~55 days, and developing balloon technologies (i.e. Super-Pressure Balloons) are expected to extend that duration to 100 days or longer; competing with satellite payloads. This relatively inexpensive platform supports a broad range of science payloads, spanning multiple disciplines (astrophysics, heliophysics, planetary and earth science.) Applications extending beyond traditional science include testing new technologies for eventual space-based application and stratospheric airships for planetary applications.

*Keywords:* balloon payloads, scientific ballooning, balloon flight operations.

## 1. Introduction

The scientific ballooning community exists worldwide, with major balloon programs and/or facilities located on every continent. A high-altitude (>20 km) balloon platform is nearly ideal for carrying out scientific observations in a space-like environment, flight qualifying novel instrumentation, and transporting humans to the edge of space. The astrophysics, heliophysics, planetary and Earth science disciplines have been instrumental in fostering a renaissance in stratospheric ballooning. The increasing interest in a robust platform to carry out a large variety of stratospheric research has driven the community to develop improved capabilities for payloads to fly at high altitudes for longer durations (> 100 days), competing with some space missions. This special issue is meant to illustrate the fact that a high-altitude balloon is pertinent to multiple disciplines, to highlight state-of-the-art balloon-based science instrumentation and to provide a reference for those interested in using this platform.

### 1.1. *Paper or Plastic: A Brief History of High-Altitude Balloons*

In the years following the first hot-air balloon flight by the Montgolfier brothers in 1783<sup>1</sup>, there was a huge push by both explorers and scientists to fly to higher altitudes over longer distances. In order to accomplish this, it was understood that improvements needed to be made in the design and materials used to make the balloon, and in the gas used to float the balloon. There was also a need to develop a robust gondola that could withstand the shock of landing. This section gives a brief history of high-altitude ballooning and science. For a more detailed history of high-altitude ballooning, one can refer to Refs. 2 and 3.

The Montgolfier balloon was made of sackcloth (linen lined with paper) and held together with buttons and a large (heavy) net of cords, and the lifting gas used was produced by combusted straw and wool. This balloon flew to an altitude of ~2 km, descending within minutes after launch. A few months later that same year, J. Charles and the Robert brothers (France) built a balloon that was inflated with hydrogen. This balloon went to an altitude of 20 km and lasted for under an hour. In December of that same year, J. Charles and the Robert brothers switched out the sackcloth with a rubberized silk cloth, impermeable to hydrogen. A valve at the top of the balloon was added to regulate the release of the gas and ballast was used for the first time to regulate ascent. The balloon traveled over 40 km and rose to an altitude of around 2 km. On this flight, the first scientific measurement (air temperature as a function of altitude) was made.

The next ~160 years showed little improvement in balloon technologies, resulting in fairly low altitudes and short duration flights. Even at these lower altitudes, there is a huge advantage over earth-based astronomical observations due to the reduced atmosphere. As a result, Sivel and Croce-Spinelli (1874) made the first astronomical measurement from a balloon. They used a spectroscope to determine the origin of the water vapor observed during ground-based spectroscopic observations of the Sun. Their measurements confirmed that the origin of the water vapor was the Earth's atmosphere, rather than water vapor in the Sun's atmosphere.<sup>2</sup>

In addition to larger balloons being flown, scientists frequently used small rubber balloons (sondes), which became available in the 1890s.<sup>4</sup> These super-pressure balloons facilitated experiments in atmospheric physics and they were used to study the Sun and cosmic rays. However, these balloons could not carry large payloads and were short-lived, as they were meant to burst when they reached a certain altitude. As such, open basket manned-flights were still the method of choice for carrying out science investigations. In 1912, Austrian physicist Victor Hess made one of the most significant discoveries in high-energy particle physics; the discovery of cosmic rays.<sup>5</sup> Even at a relatively low altitude of 4.8 km, Hess' electrosopes were able to measure an increase in the measured radiation as a function of altitude. The desire to ascend to even higher altitudes would require an improved balloon design and a pressurized gondola.

In 1935, Captain A. Stevens and Captain O. Anderson launched Explorer II from Rapid City, S.D., reaching a record breaking altitude of 22 km. This balloon used the basic design of Auguste Piccard, it used two catenary belts, one that allowed the balloon to be tethered during inflation and another to distribute and carry the load of the balloon. It also implemented an airtight cabin. On this flight, Helium rather than Hydrogen was used to inflate the balloon and eliminate the risk of explosion. This balloon was limited in altitude due to its weight, as it was still using a rubberized fabric as the balloon material. Much thinner cellophane balloons were attempted during this time, but were ultimately unsuccessful. Limited by the current-day technology, it literally took a war for the next major advancement to take place.

During World War II a significant amount of research was spent on development and large scale production of polyethylene for insulation in UHF and SHF coaxial cables of radar sets. Fortunately, Otto Winzen realized the value of using polyethylene for balloons, patenting one of the first plastic (polyethylene) balloons in 1950. These balloons, dubbed skyhooks, could reach an altitude of ~30 km, and they could carry significantly more weight (Figure 1). A short time later, R. Upson modified this balloon to have a 'natural' shape that redistributed localized stresses to integrated load tapes, allowing for much larger balloons to be fabricated. In 1970, Winzen successfully flew an 83,000 m<sup>3</sup> balloon to an altitude of 48 km, carrying a 150 g payload.<sup>2</sup>

Modern-day balloons, also called zero-pressure balloons, are very similar to those developed by Winzen in 1950 (Figure 1). These balloons have an internal pressure approximately equal to the ambient atmospheric pressure. As the partially inflated balloon rises to its floating altitude, the gas inside expands to the full volume of the balloon. To maintain altitude for the duration of the flight, temperature variations must be accounted for. If the temperature is too cold, the balloon will descend. To overcome this, ballast can be dropped. If the internal temperature is too warm, the gas is released through a vent in the balloon.

Current balloon capabilities have ushered in a new era for scientific ballooning. The amount and quality of science being performed on this platform is in-line with satellite missions and world-class ground-based observatories, with significant discoveries being made on a regular basis. Longer-duration (record is currently 55 days) and higher altitude (30-40 km) flights combined with reliable launch and recovery afforded by current capabilities have opened up this platform to a broad range of science disciplines and increasingly sophisticated measurements. In short, current balloons offer a unique in-situ platform on which to perform groundbreaking science. Smaller super-pressure balloons have flown at somewhat lower altitudes for up to 762 days. Additional advantages are related to the accessibility of the balloon platform, cost compared to satellite missions, and the reliability of launch and recovery.

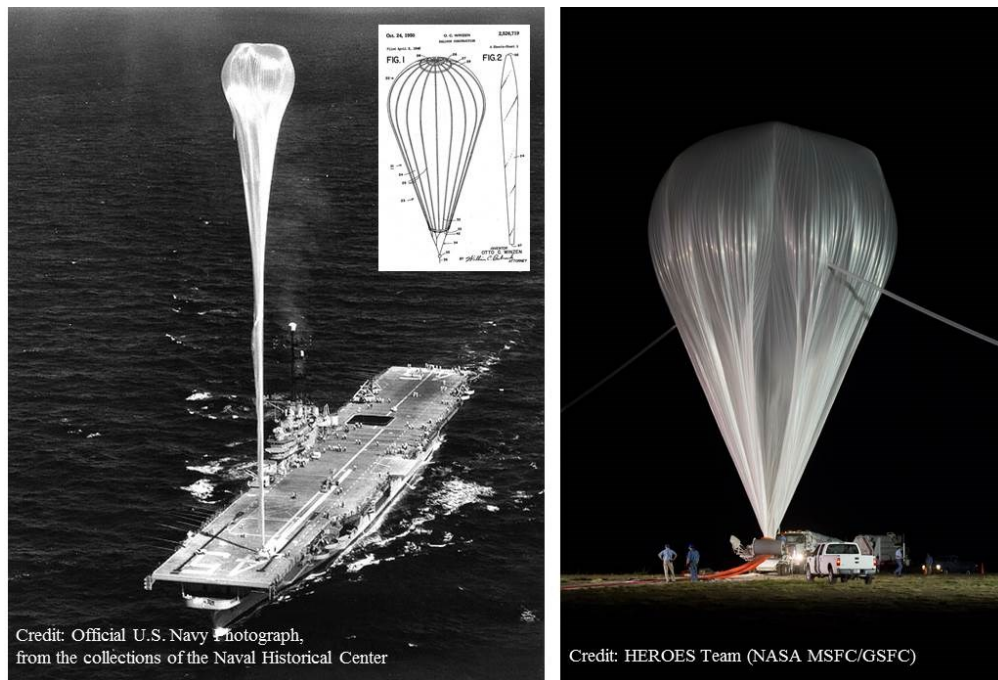


Figure 1. (Left) Photo of a Skyhook balloon just prior to launch from the USS Valley Forge in 1960. The inset is a diagram from O. Winzen's 1950 patent for a plastic balloon. (Right) Photo of a current-day zero-pressure balloon just prior to launch.

### 1.2. Advantages of a Balloon Platform: Access, Cost and Reliability

The earliest balloon-borne scientific experiments took place during the same year as the first Montgolfier balloon flight. Scientists immediately understood the value of this platform as it allowed them to make important atmospheric measurements, and it would ultimately allow for the exploration of space without the impediment of the Earth's atmosphere. Presently, this platform allows one to carry out novel science and testing of new instrumentation in a unique environment, and is relatively inexpensive to implement.

There are three types of balloons worth mentioning: latex (weather) balloons, modern zero-pressure balloons and Super-Pressure balloons (SPB). Weather balloons, generally no larger than about 3 m in diameter fully inflated, can carry a small payload of  $\sim 5.5$  kg and they are designed to burst when they reach a particular altitude. Today, these balloons can reach altitudes in excess of 27 km and they cost well under \$1000 USD. An added advantage is that they can be launched by a single individual. These balloons are regularly used by scientists, students and amateurs across the globe; making space accessible to a large portion of the population. The somewhat more expensive conventional zero-pressure balloons are much larger (up to 1.1 mcm), so they can support much large payloads (up to  $\sim 3,600$  kg). Though, these balloons are much more expensive, they are still an inexpensive alternative to a satellite payload. Large SPBs are relatively new to the science ballooning community, but they may offer a stable platform for balloon payloads to fly at lower latitudes (day/night cycles) at relatively high-altitudes for  $> 100$  days.

The cost of a new balloon payload (instruments and gondola) can range from  $\sim \$1\text{M}$  to  $\sim \$10\text{M}$ , with the majority of payloads on the lower end of this range. A NASA Small Explorer (SMEX) can cost \$120M, a Medium-Class Explorer (MIDEX) up to \$180M and Explorer (EX) up to \$200M. Flight operations for a SMEX for 2 years can be around \$3M-\$4M, compared to a balloon reflight that would typically be less than \$1M (barring major refurbishments from a previous flight).<sup>6</sup>

It is acknowledged that a satellite platform offers its own set of noteworthy advantages; however, it is difficult to overlook the fact that a significant number of balloon payloads, each potentially providing novel science, can be deployed for the cost of a single SMEX mission. They offer the advantages of the potential for multiple flights, allowing for instrument modifications and technology upgrades. Because balloon missions are inexpensive and have relatively quick turn-around times compared to satellite missions, they are also less subject to cost overrun and cancellation due to budget cuts. The fast turn-around times also make it possible to carry out science that is

time dependent. Examples of this are the balloon-borne gamma-ray measurements of Supernova 1987A, taken later in the same year (~3 to 4 months later) that the Supernova was first detected.<sup>7,8</sup>

Ease of access to ballooning, relatively low cost and the potential for quick turn-around response times create a large appeal for using this platform to perform novel science and to train new scientists. This appeal is reinforced by the availability of a range of balloon sizes to accommodate various payload types, multiple launch sites (for shorter and longer duration flights), and more sophisticated gondolas.

## 2. Science Payloads

Since the 1950s, and the invention of the ‘natural’ shaped polyethylene balloon, there has been a surge in the quality and amount of science being performed on this platform. The science that can be done from a balloon platform primarily consists of high-energy astrophysics (particle, x-ray and gamma-ray), IR/sub-mm (CMB to planetary), heliophysics, geospace and atmospheric research. The number of flights by discipline since 2003 is shown Table 1. This is a follow-on to Table 1 shown in Ref. 9, and illustrates the variety of science that has been done. Flights from 2014 have not been included, as the ballooning season was only half-way through at the time of writing this paper. Engineering flights and special projects are also not included here to keep the emphasis on science. When compiling this table, an effort was made not to include balloon sondes. The estimates in Table 1 were mainly determined from the StratoCat website.<sup>10</sup> Though these values are just estimates, they do roughly reflect the relative number of payloads by discipline launched annually worldwide.

Table 1. Breakout by science discipline of balloon launches over the past 10 years. These numbers are only estimates and do not include balloon sondes. In 2013, it is worth noting that particle astrophysics balloon flights were severely affected by NASA budget cuts that resulted in a cancellation of the Antarctica campaign that year.

Discipline	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	Total
IR/sub-mm astrophysics	6	1	2	3	2	0	5	1	1	3	1	25
X-ray/gamma-ray astrophysics	3	4	4	4	4	2	4	3	4	2	2	36
Particle astrophysics	3	3	5	4	3	2	3	1	3	2	0	29
Heliophysics	1	0	0	1	2	0	3	0	1	0	1	9
Geospace sciences	1	1	6	3	0	1	4	3	2	0	0	21
Atmosphere research	18	18	15	4	5	6	11	7	8	3	10	105
<b>Year Total (Science Flights)</b>	<b>32</b>	<b>27</b>	<b>32</b>	<b>19</b>	<b>16</b>	<b>11</b>	<b>30</b>	<b>15</b>	<b>19</b>	<b>10</b>	<b>14</b>	<b>225</b>

Atmospheric research clearly dominates in terms of the number of annual launches and these numbers are probably underestimated somewhat, as there are many smaller payloads of this type that fly on smaller balloons (sondes) much more frequently. Following atmospheric science payloads are high-energy and particle astrophysics.

The next few subsections highlight specific science missions over the past five years with emphasis on astrophysics (including planetary) and heliophysics. It is important to note that even though atmospheric and geospace research is not discussed in detail in this astronomy-focused article, there are potential cross-over technologies into planetary exploration that are germane. These payloads also provide the foundation for understanding the high-altitude balloon environment, which is relevant to all balloon payloads.

### 2.1. Astrophysics

The birth of balloon-borne astronomy began sometime in the 17<sup>th</sup> Century when scientists started flying telescopes in open-basket gondolas. Even at the fairly low altitudes afforded by these flights, the diminished atmospheric turbulence and absorption allowed for new discovery. The ability to reliably reach higher altitudes with larger payloads for longer durations has opened the door to a multitude of astronomy measurements, in multiple wavelengths that were previously inaccessible.

#### 2.1.1. IR to UV astrophysics

Over the past five years, a number of IR, visible, and UV astronomy payloads have flown. These payloads were designed to address topics ranging from star formation to the composition of comets.



Figure 2. Image of BLASTPol, a large-aperture submillimeter telescope for polarimetry.

One of the most successful payloads is the Balloon-Borne Large Aperture Submillimeter Telescope (BLAST). This telescope has the capability to study astronomical sources in the Near IR at 250  $\mu\text{m}$ , 350  $\mu\text{m}$  and 500  $\mu\text{m}$ ; providing new insight into the formation and evolution of stars, galaxies and clusters.<sup>11,12</sup> The BLAST-Pol payload developed for follow-on Antarctic campaigns successfully flew in 2010 and again in 2012<sup>13</sup> (Figure 2), and it is planned to be followed by Super BLAST-pol. The E and B Experiment (EBEX), on the other hand, measures three frequency bands in the Far IR centered at 150, 250 and 410 GHz with the goal of measuring polarization of the Cosmic Microwave Background (CMB) and, hence, the origin and structure of the Universe.<sup>14</sup> The Cosmic Foreground Explorer (COFE) is complimentary to EBEX, as it is focused on improving knowledge of CMB polarization, by characterizing the diffuse foreground microwave polarization.<sup>15</sup> The Stratospheric Terahertz Observatory (STO), launched in 2012 from Antarctica, makes use of the Far IR [CII] (1.9 THz) and [NII] (1.46 THz) lines to survey atomic, ionic and molecular clouds in the Galactic plane.<sup>16</sup> In the Near UV, the Faint Intergalactic-medium Redshifted Emission Balloon (FIREBall) mapped the diffuse emission from the Intergalactic Medium. Measurements from their flight in 2009 were able to put new constraints on the emission

from the Intergalactic Medium.<sup>17</sup>

Looking within our solar system, the Balloon Rapid Response for ISON (BRRISON), instrument consisted of a 0.8 m telescope with UV/Vis and near IR sensors, and it had the original goal of characterizing comet ISON (Figure 3).<sup>18</sup> This payload was built and flown within 10 months of the discovery of the comet, as it was able to capitalize on the hardware and experience from STO. Even though the results from the BRRISON flight were less than ideal, this somewhat ambitious payload illustrated the capability to respond to a quick turn-around mission of opportunity; a key strength of the balloon platform.

In relatively recent years, it has been realized that the balloon platform could be used to directly detect exosolar planets. Though no such missions have yet flown, there are several groups working towards this goal. A couple of examples are the Balloon Exoplanet Nulling Interferometer (BENI/BigBENI) and the Balloon-Borne Exoplanet Characterization Experiment (EchoBeach). BENI couples a visible nulling interferometer to an imaging interferometer, for direct detection of an exosolar planet and surrounding material,<sup>19</sup> while the goal of EchoBeach is to detect and characterize the atmospheres of transiting exoplanets in the Mid-IR.<sup>20</sup>

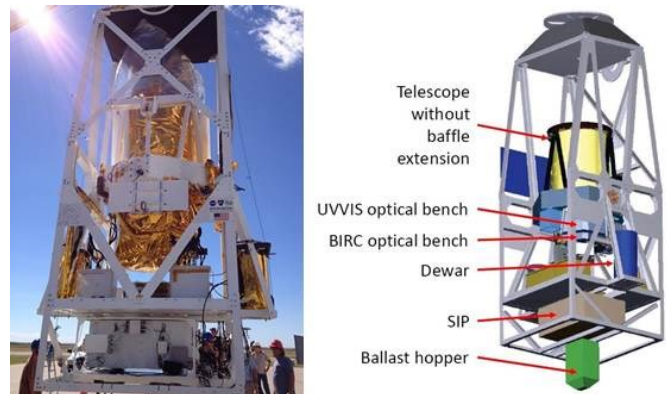


Figure 3. (Left) Photo of BRRISON taken in 2013 prior to launch. (Right) BRRISON schematic. Credit: NASA/JHUAPL (<http://brrison.jhuapl.edu/>)

### 2.1.2. X-ray and Gamma-Ray astrophysics

Following the balloon-borne detection of x-rays from the Crab Nebula in 1964,<sup>21</sup> the goal has been to fly instruments with ever-increasing resolution and improved capability. In recent years, x-ray and gamma-ray balloon payloads have focused on high resolution imaging and spectroscopy, polarization and timing.



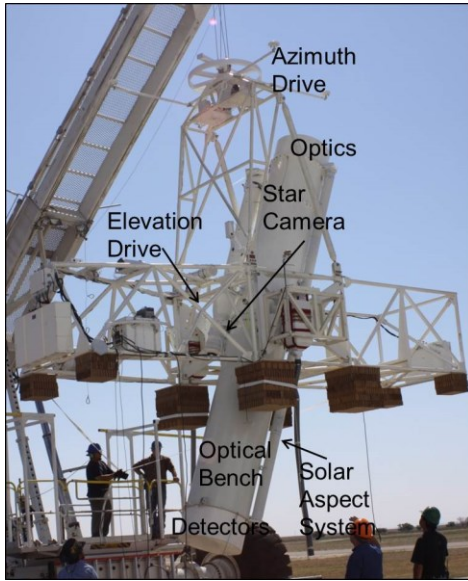


Figure 4. Photo of the HEROES Payload taken during compatibility check-out in 2013. Credit: HEROES Team.

The High Energy Replicated Optics (HERO) and later, the High Energy Replicated Optics to Explore the Sun (HEROES) telescope has been flying for over a decade. This payload, which last flew in 2013, is a hard x-ray telescope (20-75 keV) with high resolution ( $\sim 15$  arcsec, FWHM) imaging and spectroscopic capability (Figure 4).<sup>22</sup> In 2001, HERO captured the first focused hard x-ray images of galactic sources.<sup>23</sup> At higher energies, the Nuclear Compton Telescope (NCT) payload is a wide-field imaging telescope, also capable of high resolution spectroscopy and polarization measurements in the 0.2 – 10 MeV range. NCT goals are to map the positron annihilation in the Galactic Center, map the Galactic nucleosynthesis, observe compact objects such as Active Galactic Nuclei and Black Holes, and to detect the polarization of gamma-rays from compact objects and gamma-ray bursts.<sup>24</sup> Despite a launch mishap in 2012 that almost completely destroyed the payload, the NCT team has already rebuilt an improved version of their payload and will attempt to launch in 2014.

In addition to the NCT telescope, there have been several other high-energy astronomy payloads geared towards measuring hard x-ray and gamma-ray polarization launched or prepared for launch in recent years. The study of hard x-ray polarization will provide new insight into compact objects (AGN, black hole systems, neutron stars, microquasars)

and in gamma-ray sources and bursts. The science benefits of hard x-ray polarimetry are numerous, and they have been nicely summarized in Ref. 25. Recent payloads include the Polarised Gamma-ray Observer (PoGOLite),<sup>26</sup> Polarimetry for High Energy X-rays (PHENEX),<sup>27</sup> Gamma-Ray Polarimeter Experiment (GRAPE), and X-Calibur. X-Calibur, set to launch in 2014, is a hard x-ray telescope that couples grazing incidence x-ray optics, similar to that of the HERO/HEROES payload, but with a hard x-ray Compton polarimeter.<sup>28</sup> The X-Calibur is another great example of payload recycling, as it uses a sizeable portion (gondola, optics and support electronics) of the InFocus telescope; capitalizing on the experience of the InFocus team and minimizing cost.

### 2.1.3. Particle astrophysics

Particle astrophysics has a history in high-altitude ballooning that spans over 100 years. Routine discoveries in this field have resulted in unprecedented insight into the origin, acceleration and transport of Galactic cosmic rays. Several recent papers that highlight the NASA particle astrophysics program and list recent discoveries have been written.<sup>29,30</sup>



Figure 5. Photo of CRAEM VI readying for launch in Antarctica. Credit: U. of Maryland Cosmic Ray Physics Lab.

Within the past five years there have been several notable payloads in the area of particle astrophysics. The CALorimetric Electron Telescope (bCALET-2) payload, for example, was designed to observe high energy electrons (up to 100 GeV) and gamma-rays (200 MeV). The bCALET-2 test flight in 2009 resulted in a derived energy spectra of electrons and gamma-rays up at these energies.<sup>31</sup> The Cosmic Rays Energetics And Mass (CREAM V, VI) was designed to measure hydrogen to iron cosmic-ray nuclei up to hundreds of TeV (Figure 5).<sup>32</sup> This energy range is important because it includes the “knee” energy. The “knee” is a bend in the energy spectrum at high energies, around a few times  $10^{15}$  eV. The Antarctic Impulsive Transient Antenna (ANITA), which last flew in 2009, was able to put significant constraints on the Ultra-High-Energy cosmic neutrino flux.<sup>33</sup> The Trans-Iron Galactic Element Recorder, SuperTIGER

payload, designed to measure the abundances of galactic cosmic rays in the charge ( $Z$ ) range from  $\sim 10 \leq Z \leq 60$ , was the longest heavy-lift scientific balloon flight on-record (55 days in 2013). This single flight was able to detect  $\sim 4 \times 10^6$  iron nuclei (over 50 million cosmic-nuclei in total).<sup>34</sup>

Most of the payloads mentioned here have launched or will launch on a single large balloon (0.91 mcm – 1.11 mcm). One experiment has capitalized on the ability to launch and fly many smaller balloons ( $\sim 8.5$  kcm) in a single balloon campaign. This Balloon Array for RBSP Relativistic Electron Losses (BARREL) investigates electron losses from the Earth's Radiation Belts in support of the Radiation Belt Storm Probes (RBSP) mission.<sup>35</sup> Multiple balloons allow for multi-point coincident measurements with two RBSP explorers that are currently orbiting the Earth.

## 2.2. Heliophysics

The instrumentation being developed for balloon-borne astrophysics and heliophysics has significant overlap. The spectro-polarimetric observations of the atmosphere of the Sun (aka Sunrise/Sunrise II) payload shown in Figure 6, overlaps in technology with the aforementioned UV astrophysics instruments. The main instrument on Sunrise is a 1-m diameter Gregorian telescope coupled to a UV imager and filter-based magnetograph.<sup>36</sup> This payload, launched in 2009 and again in 2013, was able to map the magnetic field strength of the quiet Sun and resolve a magnetic flux tube at a resolution of better than  $\sim 0.18$  arcsecs.<sup>37</sup> HEROES, which was originally an astrophysics-only payload (HERO), was modified to observe the Sun during the day while observing astrophysical targets at night during the same balloon flight. The goal was to perform high-resolution imaging and spectroscopy to investigate the acceleration and transport of energetic electrons in solar flares and in the non-flaring solar corona.<sup>22</sup> Likewise, the Gamma-Ray Imager/Polarimeter for Solar flares (GRIPS) payload will fly an improved version of the 3D position sensitive germanium detectors that flew on the NCT payload. GRIPS, set to fly a test flight in 2014, followed by a LDB flight in Antarctica, will provide high-resolution imaging, spectroscopy and polarimetry of solar flares in the  $\sim 20$  keV – 10 MeV range.<sup>38</sup>



Figure 6. Photo of Sunrise II payload in Kiruna, Sweden. Credit: Sunrise Team.

## 3. Present Capabilities

Standard NASA scientific balloons are constructed of polyethylene film; the same type material used for plastic bags. This material is only 20 microns thick, about the same as an ordinary sandwich wrap. The film is cut into banana-peel shaped sections called gores and heat sealed together to form the balloon. Up to 180 gores are used to make NASA's largest balloons. These standard, zero-pressure balloons are open to the atmosphere at the bottom to equalize the internal pressure. Balloons can carry payloads up to  $\sim 3,600$  kg or to altitudes up to  $\sim 49$  km and/or fly for several weeks, but they cannot do all at the same time (Figure 7).<sup>39</sup>

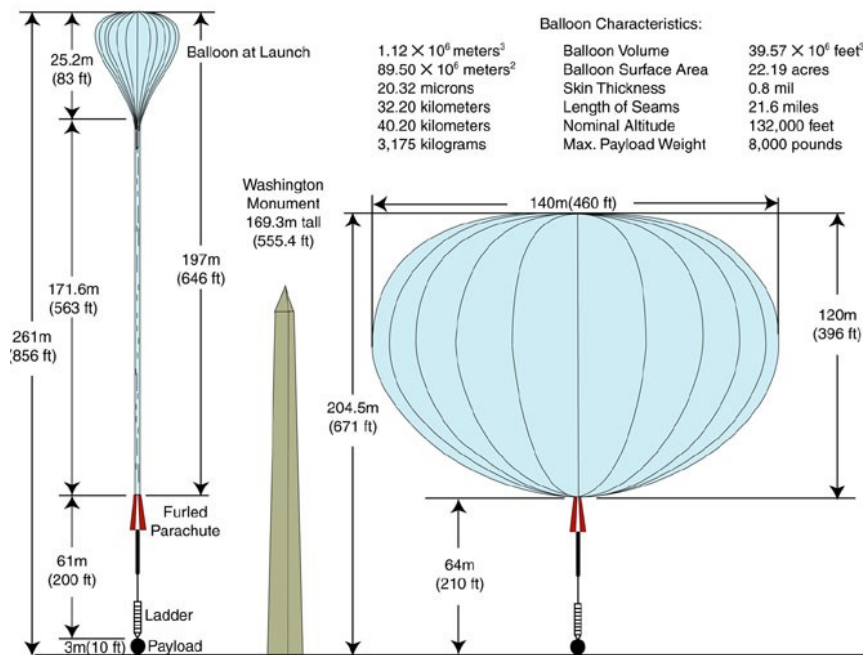


Figure 7. (Left) Diagram of a zero-pressure balloon partially filled with helium at launch, and (Right) at altitude. The Washington monument is shown for reference.

The balloon is launched by partially filling it with helium, with the payload section suspended beneath it. As the balloon rises at 5 meters per second, the helium expands, filling the balloon until it reaches float altitude in two to three hours (Figure 8).



Figure 8. (Left) Images of a partially inflated zero-pressure balloon readying for launch in Antarctica. (Right) Image of a zero-pressure balloon at altitude. As the balloon ascends, the helium expands. The tubes hanging down are “horsetail” vent ducts used to exhaust excess He from the balloon to keep it from pressurizing to failure. Credit: NASA

The balloon size required depends on the suspended load and the desired altitude. This can be seen in the load versus altitude curves (Figure 9) for NASA Standard Balloons. The largest balloon successfully flown to date has been a 1.7 mcm launched on August 25, 2002 carrying a 690 kg cosmic ray instrument. The balloon climbed to a peak altitude of 49.4 km, and was terminated normally after approximately 23 hours of flight time.



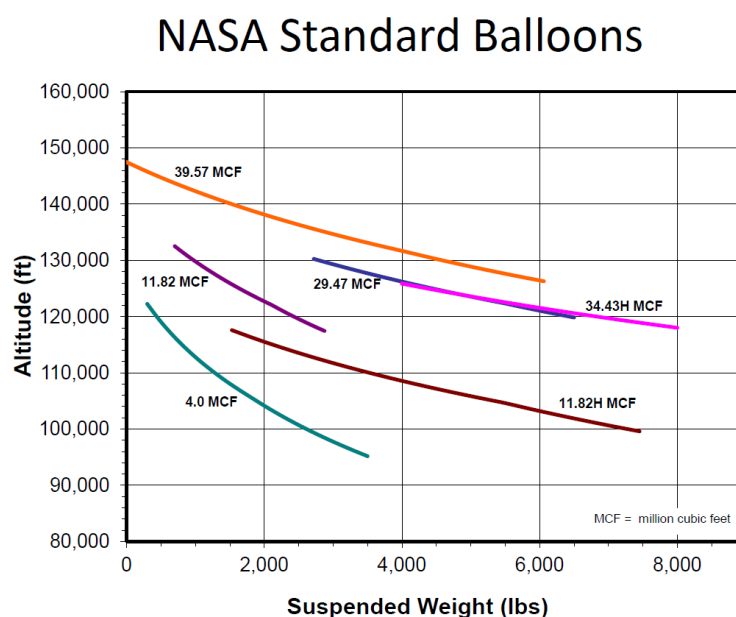


Figure 9. Plot showing the dependence of the float altitude for different size zero-pressure balloons versus the total suspended weight. The large range of balloon sizes provides an array of options to the user.

### 3.1. Flight operations

#### 3.1.1. Launch sites worldwide

The Balloon Program Office (BPO) at NASA/Wallops Flight Facility manages and supports approximately 10 to 15 flights per year (Table 2).<sup>40</sup> Flights are conducted from worldwide launch sites, as can be seen in Figure 10. Long Duration Balloon (LDB) campaigns consisting of 2 to 4 flights are launched every December in Antarctica, along with a potential summer campaign of 1 to 2 flights from Kiruna, Sweden. To date, these utilize conventional zero-pressure balloons. A LDB flight would normally traverse between continents or go around the world for one circumnavigation, and they may last up to several weeks, with the record being 55 days around Antarctica. The remaining conventional, zero-pressure flights of shorter duration (8-48 hours) are conducted from within the continental U.S. (Fort Sumner, NM for spring and fall flights, or Palestine, TX for summer flights).

Table 2. Average number of balloon flight supported by the NASA BPO in a single year from launch sites.

	Launches	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
New Zealand	1-2			LDB							I&T		
Antarctica	3-4	LDB						I&T				LDB	
Australia	3			CONV									
Fort Sumner	3-4			CONV									
Sweden	3-4	I&T				LDB							
Palestine	1-2							CONV					
Fort Sumner	6-8								CONV				

For investigations wanting to fly conventional flights, the science payload must meet certain technical interface requirements. NASA imposes safety requirements in the form of gondola structural requirements, recommendations, and certification to ensure the structural integrity of the payload prior to flight. The conventional flights are typically powered solely by batteries and use direct line-of-sight electronics for command and data downlink. LDB mission use solar arrays for power and satellite-based electronic systems are utilized for

global command uplink and telemetry data downlink. LDB flights are required to deliver the payload to the Columbia Scientific Balloon Facility (CSBF) in May of the year the payload is to fly in Antarctica for interface test validation and hang tests with the CSBF standard electronics package. After completion of integration and hang tests and just prior to shipment, a mandatory Flight Readiness Review is conducted in August to ascertain readiness of the LDB flight prior to shipment. Conventional flight investigations typically show up at Fort Sumner, NM or Palestine, TX launch facilities with sufficient time to prepare the payload for flight readiness.

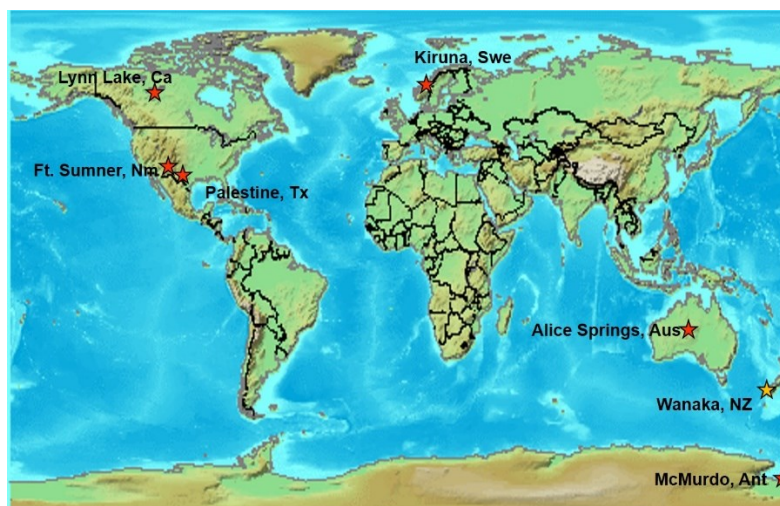


Figure 10. Map of NASA balloon launch sites. The red stars are established launch sites and the yellow stars are new.

### 3.1.2. Flight capabilities – altitude, duration, payload mass trade-off (Conventional & LDB)

Zero-pressure balloons rely on ballast equating to ~8% of the gross system mass to be dropped each night to maintain altitude as the gas cools and the volume contracts. The ultra-long duration balloon (ULDB) project is developing a 100-day duration SPB capability and has been progressing with several ground and flight tests having been conducted and more planned. The SPB is a closed cell pressurized balloon that negates the need for ballast to maintain altitude and will allow for extended flight durations approaching 100s of days and the ability to fly at lower latitudes where day/night transitions occur. The SPB has a much more stable altitude profile during the diurnal cycle as can be seen in Figure 11. A summary of LDB flights<sup>40</sup> conducted from Antarctica since 1991 can be seen in Table 3.

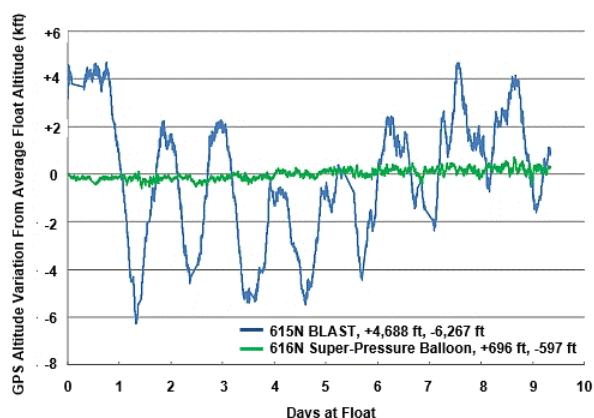


Figure 11. Flight profile for a BLAST LDB flight compared to that of a SPB.

Table 3. LDB and SPB flights from Antarctica since 1991 as a function of flight duration and total number of flights.

Flight Duration	Number of flights	Type
8-25 days	31	Single circumpolar LDB
20-32 days	6	Double circumpolar LDB
35-55 days	5	Triple circumpolar LDB
54 and 22 days	2	Super-Pressure

### 3.1.3. Recovery-overview of process

Once a decision has been made to end the balloon flight, a command is sent via the appropriate flight control system that separates the parachute and gondola from the balloon and rips a hole in the balloon expelling the gas from the balloon envelope allowing the balloon to descend to the ground.<sup>41</sup>

The payload parachute recovery system (PPRS) is in-line with the flight train and deploys immediately and automatically upon command activation, initiated at flight termination. Separated from the parachute and payload, the balloon carcass free-falls to the ground and the payload descends on the parachute (Figure 12). The parachute is sized such that the terminal impact velocity is 6-8 mps. Upon landing, the semi-automatic parachute release (SAPR) system is initiated, separating the parachute from the payload to prevent the parachute from dragging and damaging the payload. The balloon, parachute, and payload are then recovered and refurbished for future flights.



Figure 12. Photo of a descending payload on its recovery parachute. Credit: NASA

### 3.2. Gondolas

Balloon gondolas come in many sizes, shapes, masses and power requirements. Physical dimensions can be up to ~10 m in any direction (Figure 13) of any shape and have power requirements from a few watts to kilowatts. The one commonality they have is that they must survive an extreme flight environment, often more extreme than a spacecraft. The thermal environment is driven by radiation, similar to that of a spacecraft. Convection is negligible.

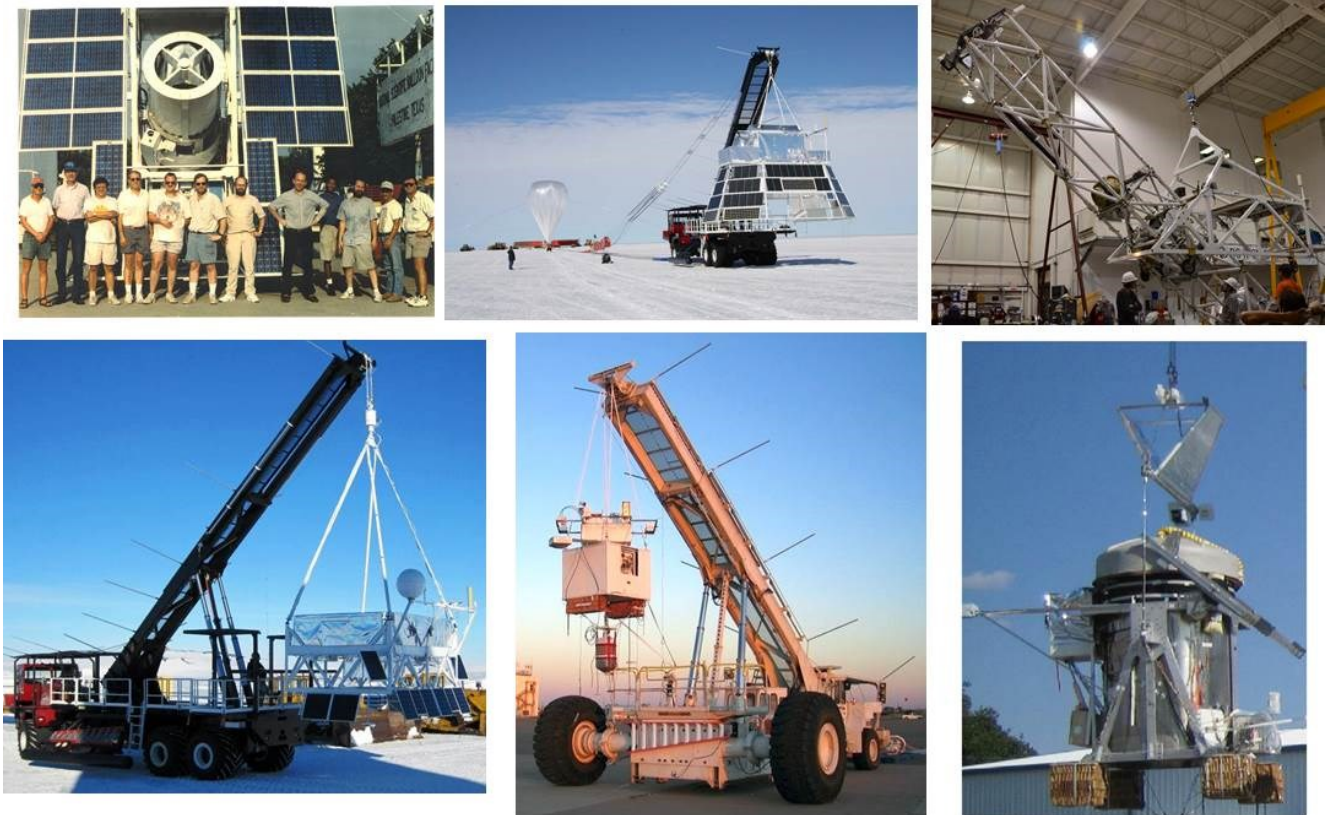


Figure 13. Photographs of example gondolas. (Top-Left) Flare Genesis (JHU/APL), (Top-Middle) Balloon-borne Experiment with a Superconducting Spectrometer, BESS-polar (KEK/NASA GSFC/Univ. Tokyo/ Kobe Univ./UMD/ISAS), (Top-Right) X-Calibur (WUSTL/NASA GSFC/Rice Univ./Nagoya Univ.), (Lower-Left) SuperTIGER (WUSTL/NASA GSFC/Caltech/UMinn), (Lower-Middle) HASP (LSU/LaSPACE/BPO), (Lower-Right) ARCADE 2 (KIPAC/NASA GSFC/Columbia Univ./INPE).



### 3.2.1. *Balloons as test beds*

Balloons serve as platforms for conducting ground breaking science as well as platforms for development of instruments to be flown on future spacecraft or other non-primary applications. Examples of spacecraft instrumentation derived from that used on balloon-flights can be found in Ref. 42. All the instruments on the Compton Gamma Ray Observatory (CGRO) were developed from balloon-flight instruments. The design of the Wilkinson Microwave Anisotropy Probe (WMAP) grew out of CMB balloon flights in the late 1980s and 1990s. The detectors on the Reuvan Ramaty High Energy Solar Spectroscopic Imager (RHESSI) were first developed for balloon borne instruments. The scintillating fiber trajectory detector for the Cosmic Ray Isotope Spectrometer on the Advanced Composition Explorer (ACE) was demonstrated first in balloon flights. Several Earth Observing System (EOS) - Aura satellite instruments trace their heritage to balloon-flight devices, as does the Thermal and Evolved Gas Analyzer (TEGA) instrument which flew on the Mars Polar Lander as part of the Mars Volatile and Climate Surveyor (MVACS) payload. The Mars Surface Laboratory carries a similar instrument.

Balloons are used as platforms for a wide variety of payloads, not all hanging down below the balloon. Examples can be seen in Figure 14 for payloads located on the top of the balloon like the cosmic microwave background TOPHAT payload or being dropped at altitude such as the Low Density Supersonic Decelerator (LDSD) or the Off-board Balloon Jammer System (OBJS). Some payloads are comprised of several smaller independent payloads such as High Altitude Student Platform (HASP) for small instrument testing as well as education for the next generations of scientists and engineers. Balloons offer great flexibility in payload configuration.

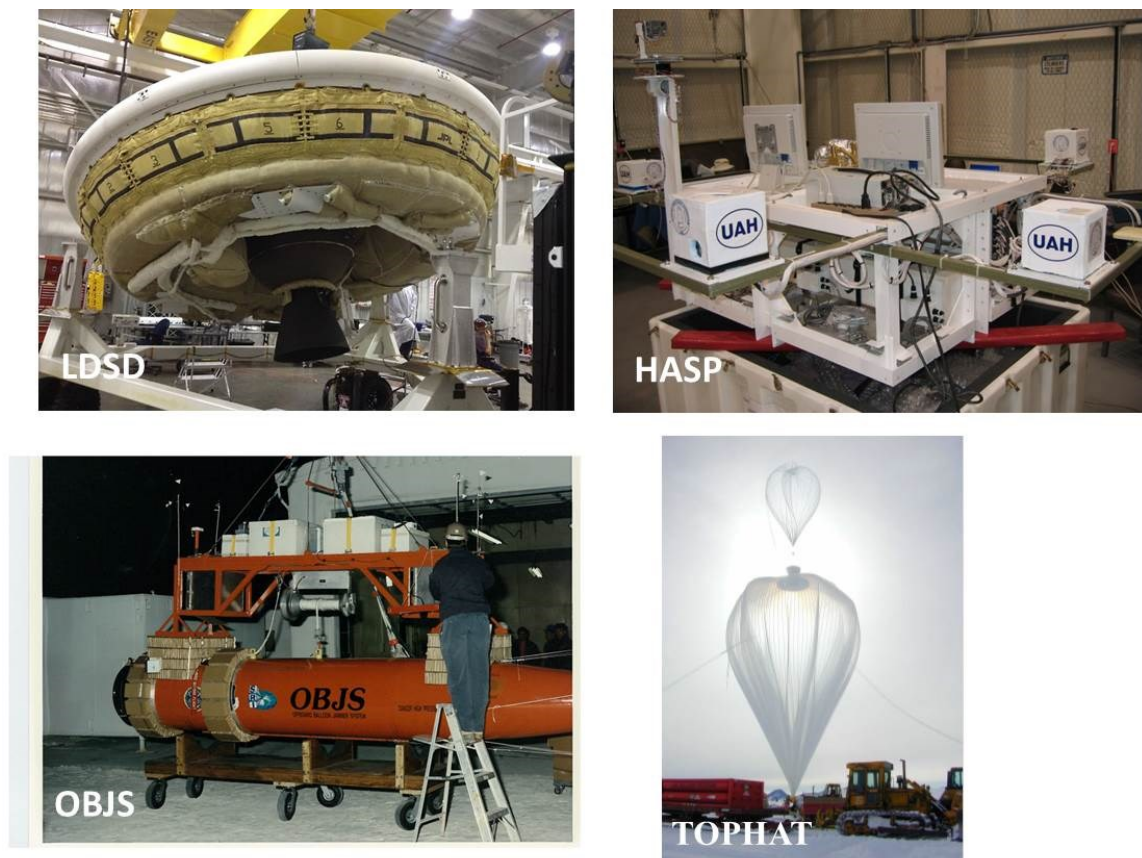


Figure 14. Examples of the wide variety and atypical payloads using balloons as platforms.



### 3.2.2. Pointing systems

High-altitude scientific balloons have been carrying payloads investigating a broad range of science disciplines. The NASA Solar Pointing System (SPS) or rotator<sup>43</sup> is provided for use on long duration scientific balloon flights. The rotator is designed for up to a 3,620 kg payload as an optional power system element to maintain maximum solar flux in conjunction with directional photovoltaic panels mounted to the gondola structure. The rotator is required to maintain pointing accuracy to within  $\pm 10$  degrees (often  $\pm 0.5$  degrees) and is intended for rough tracking of the sun for PV power – coarse azimuthal pointer. Acquisition time for target settling (180 degrees) worst case is approximately 10 minutes. The rotator is designed to provide linear stability throughout the duration of the flight with a 6 db gain margin and 30-degree phase margin. Both the upper and lower rotator universal joints provide 3-axis movement.

Year by year the investigations, and correspondingly the science instruments, have increased in complexity, as well as size and cost. Several science payloads are requiring increased pointing accuracy for scientific advances. Most recently, the branch of planetary science focused on observing exoplanets from balloons has developed, where arcsec and sub-arcsec pointing is an absolute necessity.

NASA's Wallops Flight Facility at Wallops Island, Va., has developed a new pointing system — the Wallops Arc Second Pointer (WASP)<sup>44</sup> — that can point balloon-borne scientific instruments at targets with sub arc-second accuracy and stability (Figure 15). With the help of WASP, planetary scientists will also be able to make their observations in the ultraviolet- and infrared-wavelength bands, something they really can't do from the surface of the Earth. The WASP has been designed to be quite flexible so that it can be used to help carry out a variety of diverse scientific research projects. It also saves the science team time and money by not having to design their own fine pointer. To date, three successful test flights of the WASP have been conducted, and science groups can now request the use of the WASP for their payloads.

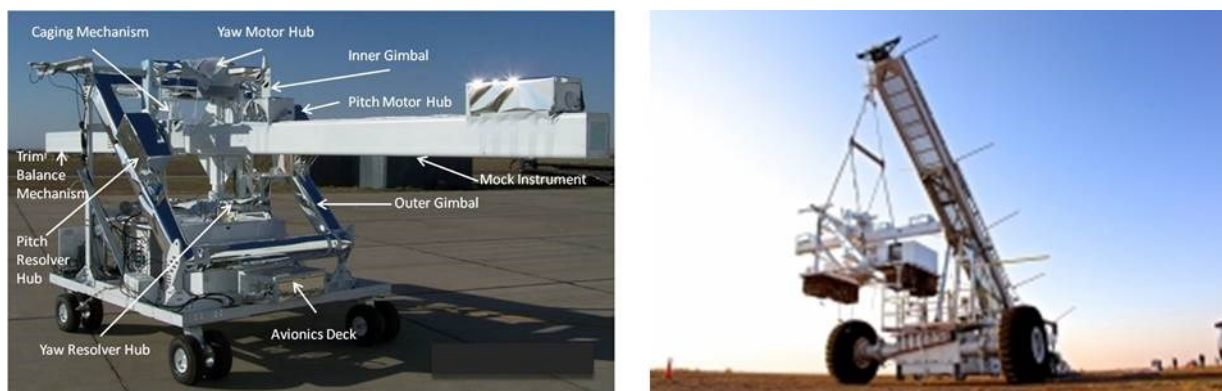


Figure 15. Photo of the Wallops Arc Second Pointer payload (WASP) (*Left*) with main components labeled, and (*right*) suspended from a launch vehicle. Credit: NASA WFF.

### 3.2.3. Telemetry

**LOS (Line-of-Site):** L-Band or S-Band telemetry can be made available for science data monitoring while within line-of site of the launch site. This is provided through the NASA provided Consolidated Instrument Package (CIP). Serial isolation to this transmitter is required. The experimenter is responsible for any encoding the signal may require (i.e. bi-phase, NRZ-M, etc.) as well as setting of proper signal levels into the transmitter. Data rates up to 1 Megabit per second (Mbps) direct return are possible.

**OTH (over-the-horizon) Iridium:** Iridium provides global forward and return telemetry with the balloon via a network of Low Earth Orbiting (LEO) satellites. Commands (forward TM) can be sent from both the Operational Control Center (OCC) at Palestine, TX and during testing from the Remote Operational Control Center (ROCC) at the launch site. Data (return TM) is received at the OCC and can be tested from the ROCC. Data is usually received within a few minutes of transmission from the balloon depending upon the load of network traffic. The science port operates at 2400 baud as a packetized system, and return data throughput is one 255 byte packet every 15 minutes when the flight Iridium terminal is logged into the network.

OTH (over-the-horizon) Tracking and Data Relay Satellite System (TDRSS): Nominal TDRSS support for LDB offers 6-8 kilo-bit return telemetry continuously (the low rate science interface is also available) using the OMNI-directional antenna. The NASA provided Support Instrument Package (SIP) records all science data onto its flight computer hard drives, which are recovered only at the end of the flight. Provisions for playing back science data in case of TDRSS outages should be handled by the science flight computer if so desired. These data can be recovered in flight by utilizing the TDRSS SA (Single Access) mode at higher data rates or throttling back data rates to continue to receive real-time data. A higher data rate TDRSS capability is also available. A High Gain Antenna (HGA) allowing science to transmit up to approximately 92 kbps using a 115,200 baud serial interface can be included.

#### **4. The Future of Ballooning**

Looking towards the future of ballooning, there are several areas that would benefit from continued development, including: (1) improved balloon structures that can fly for longer periods at high altitudes, in order to achieve Ultra-Long Duration Balloon (ULDB) durations, (2) the capability to support larger payloads, (3) increased telemetry data bandwidth, (4) lighter-weight gondolas and instrumentation (5) fine pointing capability and (6) trajectory control.

As mentioned previously, the vented zero-pressure (in equilibrium with the atmosphere) balloons used today have changed only incrementally from those introduced in the 1950's.<sup>45</sup> Since that time, large polyethylene balloons have been employed for a variety of scientific and technological pursuits. They offer a unique capability for frequent access to near-space for science and technology instruments ranging in mass from a few kilograms to thousands of kilograms. They traditionally carried payloads for 1 - 2 days, but in the early 1990's NASA extended balloon flight durations to 10 - 20 days by conducting launches in the constant sunlight during Antarctic summers. These LDB flights employing zero-pressure polyethylene balloons identical to those utilized for conventional flights are severely limited in duration by gas loss during day-night transitions.

The inauguration of LDB flights around Antarctica provided a sea change in scientific ballooning. These circumpolar flights have been spectacularly successful, with many investigations utilizing multiple flights of payloads that are recovered, refurbished, and reused to minimize life-cycle costs.<sup>46</sup> The attainment of 25 - 32 day and 35 - 55 day flights, respectively, in two and three circumnavigations of the Antarctic continent has greatly increased the expectations of scientific users. Requests for participation in the Antarctic LDB program, a NASA partnership with the U.S. National Science Foundation Office of Polar Programs (NSF/OPP), exceed the current capacity of two or three flights per annual campaign.

##### **4.1. Ultra-long duration ballooning**

The constant sunlight during local summer in the Polar Regions allows zero-pressure balloons to maintain their float altitudes for long periods of time. However, mid-latitude flights using zero-pressure balloons are limited to only a few days, because ballast must be dropped at each day-night transition to maintain float altitude. The volumes of zero-pressure balloons used for conventional and polar LDB flights change as the ambient atmospheric pressure changes, causing a very large altitude droop at night (Figure 11). By contrast, a SPB maintains nearly constant volume, thereby enabling LDB flights in non-polar latitudes. These new balloons will carry sufficiently heavy payloads to high altitudes, so they will undoubtedly bring another sea change in scientific ballooning by enabling mid-latitude LDB missions.

The 0.198 mcm (7 million cubic feet (mcf)) SPB test flight launched in December 2008 and terminated in February 2009 after 54 days aloft during its third circumnavigation of Antarctica shows the promise of this entirely new launch vehicle (Figure 16). It achieved a new flight duration record for a balloon of this size and type, and its performance (altitude and differential pressure) remained steady with no gas loss. It was terminated only because its flight path was projected to go off the continent. Otherwise it could have flown considerably longer. This new capability will enable cost effective observations in a variety of astrophysics and other disciplines. The frequent access to space provided by smaller space missions (e.g., Small Explorers - SMEX) accelerated scientific and technical innovation in the space sciences. Balloon-borne payloads provide similar

benefits at still lower cost, and a new generation of ULDB missions with 100 days or more of observing time near the top of the atmosphere seems imminent.

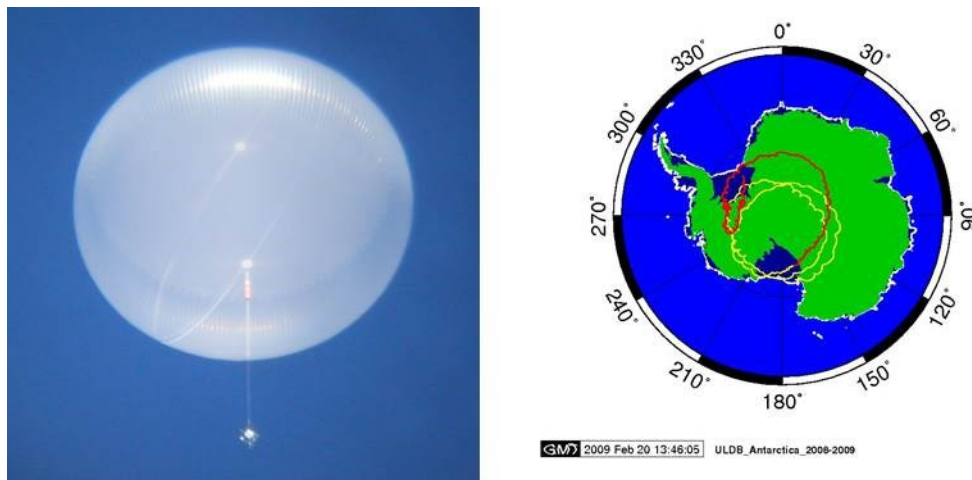


Figure 16. (Left) Photograph of the 0.198 mcm SPB at float. (Right) The 0.198 mcm balloon's 54-day flight trajectory over Antarctica showing turnaround of the stratospheric wind polar vortex.

#### 4.2. Super-pressure balloons

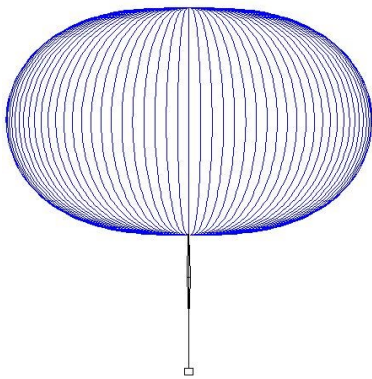


Figure 17. Schematic of the pumpkin-shaped SPB.

The NASA design for a super-pressure balloon has a pumpkin shape with the inflated height about 0.6 of the inflated diameter (Figure 17). The 0.533 mcm (18.8 mcf) SPB has 280 gores, each with a length of 150 m. The inflated diameter is 114.6 m, and the uninflated diameter is 71 m. The shell film thickness is  $\sim 38$  microns. The final weight of the balloon is 2,316 kg. The total length of Load Tape Tendons in the balloon is  $\sim 42$  km (26 miles). The amount of film visually inspected, re-rolled and dispensed for this balloon is  $> 120,773 \text{ m}^2$  (30 acres) of film. The minimum amount of walking just to seal the balloon is  $\sim 16.8$  km (55 miles). The balloon shipping box has dimensions of  $\sim 4.9 \text{ m} \times \sim 1.8 \text{ m} \times \sim 1.6 \text{ m}$ . The gross weight of the balloon in the box is  $\sim 4,006$  kg.

The most significant challenges in SPB development have been overcome and certification of a science-capable 0.533 mcm (18.8 mcf) SPB is underway. It is planned to launch this balloon in December 2014 with a science instrument and, if appropriate, they would be allowed to leave the continent and continue flying over the Southern Ocean after circumnavigating Antarctica several times. Since the SPB volume does not depend on its temperature, it is not subject to temperature-driven altitude variations. It should maintain essentially the same altitude throughout its flight, whether in full sun or in the dark, because it is essentially insensitive to the amount of infrared albedo from the Earth. This is in stark contrast to Antarctic LDB flights with zero-pressure balloons, which exhibit large altitude excursions, even with constant sun exposure due to the varying Sun angle.

SPBs enable long-duration flights at mid-latitude or ultra-long-duration flights from Antarctica without the need for additional supporting technology developments. Such flights offer important new opportunities to employ balloons for world-class science investigations in diverse fields, including Astrophysics, Heliophysics, and Earth Science. The current development plan includes increasing the SPB volume to 0.736 mcm (26 mcf), in order to carry heavier payloads and to reach higher float altitudes for lighter payloads.

#### 4.3. Stratospheric airships

Airships are lighter-than-air vehicles that can generate their own thrust for maneuvers allowing for trajectory control or station-keeping. The external structure or envelope of such craft fall into three categories: rigid, semi-rigid, and non-rigid. Rigid airships are built with material stretched on a full structural frame. The Zeppelins are

an example using light alloy girders to support gas cells. Semi-rigid craft typically have a lower arced keel that maintains the ship's shape. Non-rigid ships have envelopes that are supported by the gas pressure alone (e.g., the blimps). This is the type used primarily for weight savings on stratospheric airships. "Hybrid" designs rely on buoyancy from helium to stay aloft and an aerodynamically shaped airfoil that provides additional lift. In the hybrid airship, the three forces of buoyancy, lift, and thrust are combined to direct the craft.

The Department of Defense (DOD) and the Intelligence communities have been the largest funding sources for stratospheric airships to date, and it is still in its infancy. Most requirements have been in areas of application in Intelligence, Surveillance and Reconnaissance (ISR). To date over \$500M has been invested by DOD towards developing stratospheric airships with mixed results. Only two (see Figure 18) prototype stratospheric airships have been flown with only the HiSentinel<sup>47</sup> successfully achieving flight altitude. Once reliable airships are fully developed, their advantages in greater duration and recoverability will make them a very powerful tool for scientific research across an unusually broad spectrum.

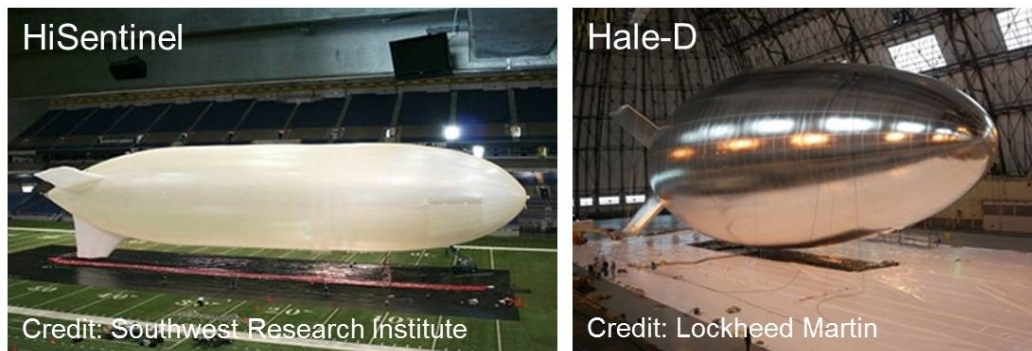


Figure 18. Images of prototype stratospheric airships HiSentinel and Hale-D.

It is important to recognize that the use of stratospheric airships for science is focused on those applications that existing free-flying balloon platforms either cannot meet at all or that provide substantially less attractive performance in terms of flight duration, reusability or geographic access. Even a modest telescope at stratospheric altitudes would provide image quality that could compete with space-based telescopes.

#### 4.4. *Trajectory control*

The NASA Balloon Program conducts flight operations on a local, regional and global basis. Balloon missions often over-fly population concentrations, and as a result they can pose additional risk to the populations below. NASA has three options once this occurs: 1) reduce the risk by various means, 2) accept the risk, 3) terminate the mission prior to reaching the population center or 4) cancel the mission. Since NASA is in the business of conducting scientific missions, reducing the risk to acceptable levels is always the first choice.

The SPB has been identified as a carrier with the potential for significant earth and space science return from Ultra Long Duration Balloon (ULDB) flights. However, a balloon carrier launched from a typical mid-latitude site will expose populations beneath the float path to non-negligible and potentially unacceptable risk levels. The black line in Figure 19 shows the approximate mean float path of a balloon carrier launched from Alice Springs, Australia, superimposed on a global city population distribution map.<sup>48</sup> Ground casualty risk due to over-flight of population distribution spikes from Johannesburg, Pretoria, Rio de Janeiro, and Sao Paulo were considered unacceptable for the conduct of previous ULDB test flights. Mission flight-termination rules were established to preclude over-flight, but would have exposed valuable payload hardware to unacceptable risk of loss.



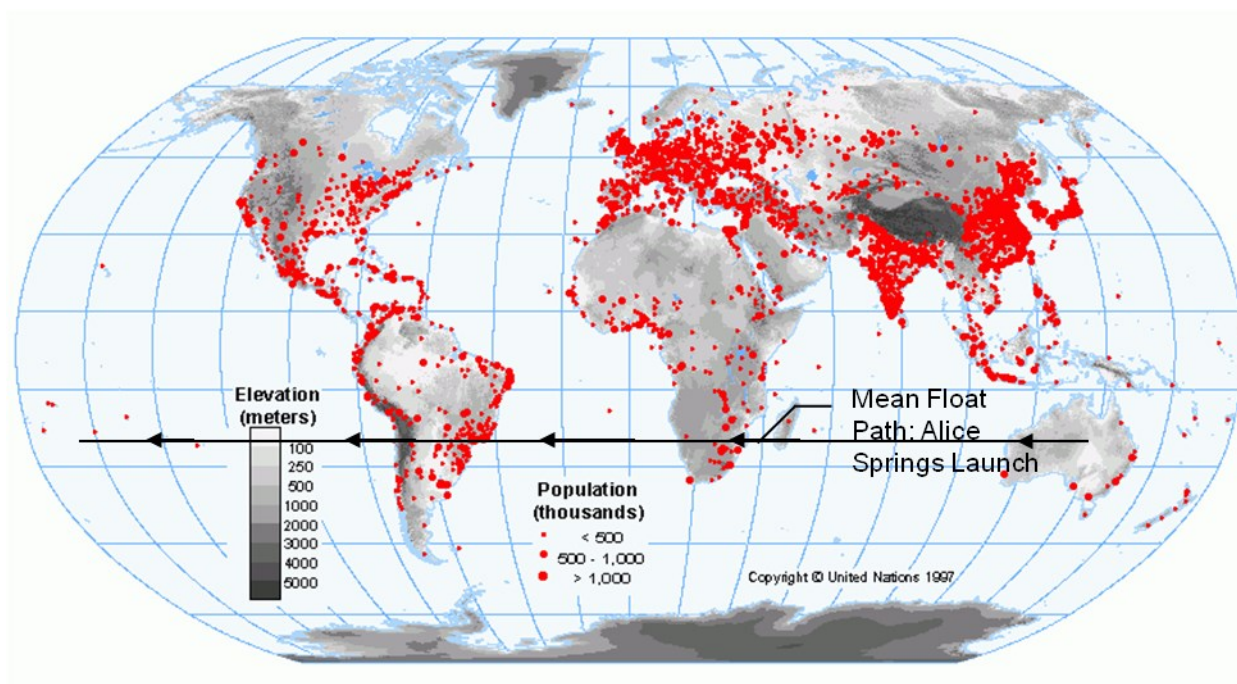


Figure 19. Approximate Mean Float Path of a Balloon Carrier Launched from Alice Springs, Australia.

One way to reduce over-flight risk is to avoid the population centers by altering the trajectory of the balloon. Several investigations have been performed looking at viable trajectory control systems. The analytical investigations have included propulsive and non-propulsive trajectory control systems, with each technical approach identifying deficiencies in the other approach and strengths of its own. However, these have continued to be analytical treatises with no actual hardware being flown and no performance and engineering data having been collected at altitudes of interest.<sup>49,50</sup> Recent interest by NASA as well as the DOD/Intelligence communities has revived interest (although contrary goals) in developing methods for trajectory control.

## 5. Conclusions

The flexibility, reliability and relatively low-cost of the high-altitude balloon platform makes for an attractive means of carrying out novel science in a space-like environment across multiple disciplines. Existing balloons are capable of carrying large payloads to high altitudes for flight durations lasting tens of days. The longest LDB flight to date was that of SuperTIGER in 2012-2013 on a vented zero-pressure balloon. This payload weighed around 2,025 kg (not including flight straps)<sup>51</sup> and flew to a maximum altitude of ~39.6 km. The entire flight lasted for just over 55 days.<sup>34</sup> The development of the SPB holds promise for achieving even longer flights launching from Antarctica (> 100 days), and LDB flights from mid-latitude launch sites. This capability, combined with improved payload pointing, light-weight gondolas and more sophisticated instrumentation will enable scientists to make new discoveries and develop novel instrumentation suitable for orbital missions. This platform will also continue to provide a training ground for the next generation of scientists and engineers.

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